YUMS-95-9
SNUTP-95-030
hep-ph/9504369
March 1995

Implications of the Recent Top Quark Discovery on Two Higgs Doublet Model

GYE T. PARK

Department of Physics, Yonsei University

Seoul, 120-749, Korea

Abstract

Concentrating on the impact of the very recent top quark discovery, we perform a combined analysis of two strongest constraints on the 2 Higgs doublet model, one coming from the recent measurement by CLEO on the inclusive branching ratio of $b \to s\gamma$ decay and the other from the recent LEP data on $Z \to b\bar{b}$ decay. We have included the model predictions for one-loop vertex corrections to $Z \to b\bar{b}$ through ϵ_b. We find that the ϵ_b constraint excludes most of the less appealing window $\tan\beta \lesssim 1$ at 95%C. L. for the measured top mass from CDF, $m_t = 176 \pm 8 \pm 10$ GeV. Moreover, it excludes $\tan\beta \lesssim 2$ at 95%C. L. for $m_t \gtrsim 176$ GeV. Combining with the $b \to s\gamma$ constraint, only very heavy charged Higgs ($\gtrsim 670$ GeV) is allowed by the measured m_t from CDF.

Very recently, the CDF Collaboration from Fermi Laboratory has finally announced their observation of top quark production in $\overline{p}p$ collisions with the measured top mass [1], $m_t = 176\pm8\pm10$ GeV. The top quark discovery now leaves the Standard Higgs mass m_H the only unknown parameter in the Standard Model(SM). The unknown m_t has long been one of the biggest disadvantages in studying the phenomenology of the SM and its extensions of interest. Now that m_t becomes known at last, one should be able to narrow down the values of m_t in the vicinity of the above central value. Despite the remarkable successes of the SM in its complete agreement with current all experimental data, there is still no experimental information on the nature of its Higgs sector. The 2 Higgs doublet model(2HDM) is one of the mildest extensions of the SM, which has been consistent with experimental data. In this letter, we would like to present the implications of the top quark discovery on the 2HDM in view of the two strongest constraints present in the model, namely, the ones from the flavor-changing radiative decay $b \to s\gamma$ and $Z \to b\overline{b}$ decay. In the 2HDM to be considered here, the Higgs sector consists of 2 doublets, ϕ_1 and ϕ_2, coupled to the charge -1/3 and +2/3 quarks, respectively, which will ensure the absence of Flavor-Changing Yukawa couplings at the tree level [2]. The physical Higgs spectrum of the model includes two CP-even neutral Higgs(H^0, h^0), one CP-odd neutral Higgs(A^0) , and a pair of charged Higgs($H^\pm$). In addition to the masses of these Higgs, there is another free parameter in the model, which is $\tan\beta \equiv v_2/v_1$, the ratio of the vacuum expectation values of both doublets.

After the first observation by CLEO on the exclusive decay $B \to K^*\gamma$[3], CLEO has recently measured for the first time the inclusive branching ratio of $b \to s\gamma$ decay to be at 95% C. L. [4],

$$1 \times 10^{-4} < B(b \to s\gamma) < 4 \times 10^{-4}.$$

This follows the renewed surge of interests on the $b \to s\gamma$ decay, spurred by the CLEO bound $B(b \to s\gamma) < 8.4 \times 10^{-4}$ at 90% C.L. [5], with which it was pointed out in Ref. [6]

that the CLEO bound can be violated due to the charged Higgs contribution in the 2HDM and the Minimal Supersymmetric Standard Model(MSSM) basically if $m_{H^\pm}$ is too light, excluding large portion of the charged Higgs parameter space. It has certainly proven that this particular decay mode can provide more stringent constraint on new physics beyond SM than any other experiments[7]. However, it turns out in the 2HDM that the only constraint competing with the one from $b \to s\gamma$ comes from the LEP data on the $Z \to b\bar{b}$ decay[8]. As we know, with the increasing accuracy of the LEP measurements, it has become extremely important performing the precision test of the SM and its extensions*. Among several different schemes to analyze precision electroweak tests, we choose a scheme introduced by Altarelli et. al. [10, 11] where four variables, $\epsilon_{1,2,3}$ and ϵ_b are defined in a model independent way. These four variables correspond to a set of observables Γ_l, Γ_b, A^l_{FB} and M_W/M_Z. Among these variables, ϵ_b encodes the vertex corrections to $Z \to b\bar{b}$.

In the 2HDM and the MSSM, $b \to s\gamma$ decay receives significant contributions from penguin diagrams with $W^\pm - t$ loop, $H^\pm - t$ loop [12] and the $\chi^\pm_{1,2} - \tilde{t}_{1,2}$ loop [13] only in the MSSM. The expression used for $B(b \to s\gamma)$ in the leading logarithmic (LL) calculations is given by [14]

$$\frac{B(b \to s\gamma)}{B(b \to ce\bar{\nu})} = \frac{6\alpha}{\pi} \frac{\left[\eta^{16/23} A_\gamma + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) A_g + C\right]^2}{I(m_c/m_b)\left[1 - \frac{2}{3\pi}\alpha_s(m_b) f(m_c/m_b)\right]}, \tag{1}$$

where $\eta = \alpha_s(M_W)/\alpha_s(m_b)$, I is the phase-space factor $I(x) = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$, and $f(m_c/m_b) = 2.41$ the QCD correction factor for the semileptonic decay. C represents the leading-order QCD corrections to the $b \to s\gamma$ amplitude when evaluated at the $\mu = m_b$ scale [14]. We use the 3-loop expressions for α_s and choose Λ_{QCD} to obtain $\alpha_s(M_Z)$ consistent with the recent measurements at LEP. In our computations we have used: $\alpha_s(M_Z) = 0.118$,

*A standard model fit to the latest LEP data yields the top mass, $m_t = 178 \pm 11^{+18}_{-19}$ GeV [9], which is in perfect agreement with the measured top mass from CDF.

$B(b \to ce\bar{\nu}) = 10.7\%$, $m_b = 4.8$ GeV, and $m_c/m_b = 0.3$. The A_γ, A_g are the coefficients of the effective $bs\gamma$ and bsg penguin operators evaluated at the scale M_W. Their simplified expressions are given in Ref. [15] in the justifiable limit of negligible gluino and neutralino contributions [13] and degenerate squarks, except for the $\tilde{t}_{1,2}$ which are significantly split by m_t. Regarding large uncertainties in the LL QCD corrections, which is mainly due to the choice of renormalization scale μ and is estimated to be $\approx 25\%$, it has been recently demonstrated by Buras *et al.* in Ref. [16] that the significant μ dependence in the LL result can in fact be reduced considerably by including next-to-leading logarithmic (NLL) corrections, which however, involves very complicated calculations of three-loop mixings between cetain effective operators and therefore have not been completed yet. In Fig. 1 we present the excluded regions in $(m_{H^\pm}, \tan\beta)$-plane in the 2HDM for $m_t = 163$, and $176\,\mathrm{GeV}$, which lie to the left of each dotted curve. The m_t values are of course the central value and the lower limit from the CDF. The contours are obtained using the new 95% C. L. upper bound $B(b \to s\gamma) = 4 \times 10^{-4}$. As expected, the new CLEO bound excludes a large portion of the parameter space. We have also imposed in the figure the lower bound on $\tan\beta$ from $\frac{m_t}{600} \lesssim \tan\beta \lesssim \frac{600}{m_b}$ obtained by demanding that the theory remain perturbative[17]. We see from the figure that at large $\tan\beta$ one can obtain a lower bound on $m_{H^\pm}$ for each value of m_t. And we obtain the bounds , $m_{H^\pm} \gtrsim 672, 843\,\mathrm{GeV}$ for $m_t = 163, 176\,\mathrm{GeV}$, respectively.

Following Ref. [10], ϵ_b is defined from Γ_b, the inclusive partial width for $Z \to b\bar{b}$, as

$$\epsilon_b = \frac{g_A^b}{g_A^l} - 1 \tag{2}$$

where g_A^b (g_A^l) is the axial-vector coupling of Z to b (l). In the SM, the diagrams for ϵ_b involve top quarks and $W^\pm$ bosons [18], and the contribution to ϵ_b depends quadratically on m_t ($\epsilon_b = -G_F m_t^2/4\sqrt{2}\pi^2 + \cdots$). In supersymmetric models there are additional diagrams

involving Higgs bosons and supersymmetric particles. The charged Higgs contributions have been calculated in Refs. [19, 8] in the context of the 2HDM, and the contributions involving supersymmetric particles in Refs. [21, 20]. The main features of the additional supersymmetric contributions are: (i) a negative contribution from charged Higgs–top exchange which grows as $m_t^2/\tan^2\beta$ for $\tan\beta \ll \frac{m_t}{m_b}$; (ii) a positive contribution from chargino-stop exchange which in this case grows as $m_t^2/\sin^2\beta$; and (iii) a contribution from neutralino(neutral Higgs)–bottom exchange which grows as $m_b^2\tan^2\beta$ and is negligible except for large values of $\tan\beta$ (*i.e.* , $\tan\beta \gtrsim \frac{m_t}{m_b}$). ϵ_b is closely related to the real part of the vertex correction to $Z \to b\bar{b}$, ∇_b defined in Ref[21]. The additional diagrams involving $H^\pm$ bosons have been calculated in Ref[8, 20, 21, 19]. The charged Higgs contribution to ∇_b is given as [21]

$$\nabla_b^{H^\pm} = \frac{\alpha}{4\pi\sin^2\theta_W}\left[\frac{2v_L F_L + 2v_R F_R}{v_L^2 + v_R^2}\right] , \tag{3}$$

where $F_{L,R} = F_{L,R}^{(a)} + F_{L,R}^{(b)} + F_{L,R}^{(c)}$ and

$$F_{L,R}^{(a)} = b_1\left(M_{H^+}, m_t, m_b\right) v_{L,R}\lambda_{L,R}^2 , \tag{4}$$

$$\begin{aligned} F_{L,R}^{(b)} = & \left[\left(\frac{M_Z^2}{\mu^2}c_6\left(M_{H^+}, m_t, m_t\right) - \frac{1}{2} - c_0\left(M_{H^+}, m_t, m_t\right)\right) v_{R,L}^t \right. \\ & \left. + \frac{m_t^2}{\mu^2}c_2\left(M_{H^+}, m_t, m_t\right) v_{L,R}^t\right] \lambda_{L,R}^2 , \end{aligned} \tag{5}$$

$$F_{L,R}^{(c)} = c_0\left(m_t, M_{H^+}, M_{H^+}\right)\left(\frac{1}{2} - \sin^2\theta_W\right)\lambda_{L,R}^2 , \tag{6}$$

where μ is the renormalization scale and

$$v_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W , \quad v_R = \frac{1}{3}\sin^2\theta_W , \tag{7}$$

$$v_L^t = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W , \quad v_R^t = -\frac{2}{3}\sin^2\theta_W , \tag{8}$$

$$\lambda_L = \frac{m_t}{\sqrt{2} M_W \tan\beta}\,, \quad \lambda_R = \frac{m_b \tan\beta}{\sqrt{2} M_W}\,. \tag{9}$$

The b_1 and $c_{0,2,6}$ above are the reduced Passarino-Veltman functions[21, 22]. In our calculation, we neglect the neutral Higgs contributions to ∇_b which are all proportional to $m_b^2 \tan^2\beta$ and become sizable only for $\tan\beta > \frac{m_t}{m_b}$ and very light neutral Higgs $\lesssim 50\,\mathrm{GeV}$, but decreases rapidly to get negligibly small as the Higgs masses become $\gtrsim 100\,\mathrm{GeV}$[19]. We also neglect oblique corrections from the Higgs bosons just to avoid introducing more paramters. However, this correction can become sizable when there are large mass splittings between the charged and neutral Higgs, for example, it can grow as $m_{H^\pm}^2$ if $m_{H^\pm} \gg m_{H^0,h^0,A^0}$. Although $\tan\beta \gg 1$ seems more appealing because of apparent hierarchy $m_t \gg m_b$, there are still no convincing arguments against $\tan\beta < 1$. Our goal here is to see if one can put a severe constraint from ϵ_b in this region. In Fig. 1 we show the contours (solid) of a predicted value of $\epsilon_b = -0.00733$, which is the LEP lower limit at 95%C. L.[23]. The excluded regions lie below each solid curve for given m_t. For $m_t = 176(163)\,\mathrm{GeV}$, $\tan\beta \lesssim 2.0(0.6)$ is ruled out at 95%C. L. for $m_{H^\pm} \lesssim 1000\,\mathrm{GeV}$. We note that these strong constraints for $\tan\beta \lesssim 1$ stem from large deviations of ϵ_b from the SM prediction, which grows as $m_t^2/\tan^2\beta$ as explained above. Combining both $b \to s\gamma$ and ϵ_b constraints, only the region above the solid curve and to the right of the dotted curve survive. For $m_t = 176(163)\,\mathrm{GeV}$, $\tan\beta \gtrsim 2.0(0.6)$ and $m_{H^\pm} \gtrsim 843(672)\,\mathrm{GeV}$ are allowed at 95%C. L.

We have also considered other constraints from low-energy data primarily in $B-\overline{B}, D-\overline{D}, K-\overline{K}$ mixing that exclude low values of $\tan\beta$[17, 24]. But it turns out that none of them can hardly compete with the present ϵ_b constraint[25]. Nevertheless, the CLEO bound is still by far the strongest constraint present in the charged Higgs sector of the model for $\tan\beta > 1$. Therefore, we find that $b \to s\gamma$ and ϵ_b serve as the presently strongest and complimentary constraints in 2HDM.

In conclusion, we study the implications of the top quark discovered very recently by CDF by performing a combined analysis of two strongest constraints on the 2 Higgs doublet model, one coming from the recent measurement by CLEO on the inclusive branching ratio of $b \to s\gamma$ decay and the other from the recent LEP data on $Z \to b\bar{b}$ decay. We have included the model predictions for one-loop vertex corrections to $Z \to b\bar{b}$ through ϵ_b. We find that the ϵ_b constraint excludes most of the less appealing window $\tan\beta \lesssim 1$ at 95%C. L. for the measured top mass, $m_t = 176 \pm 8 \pm 10$ GeV. Moreover, it excludes $\tan\beta \lesssim 2$ at 95%C. L. for $m_t \gtrsim 176$ GeV. Combining with the $b \to s\gamma$ constraint, only very heavy charged Higgs ($\gtrsim 670$ GeV) is allowed by the measured m_t from CDF.

ACKNOWLEDGEMENTS

The author thanks Professor Jihn E. Kim for very helpful discussions. This work has been supported in part by Yonsei University Faculty Research Grant and in part by the Center for Theoretical Physics, Seoul National University.

References

[1] CDF Collaboration, Report No. FERMILAB-PUB-95/022-E (hep-ex/9503002).

[2] S. Glashow and S. Weinberg, Phys. Rev. D **15** (1977) 1958.

[3] R. Ammar *et al.* (CLEO Collab.), Phys. Rev. Lett. **71** (1993) 674.

[4] E. Thorndike (CLEO Collaboration), talk given at XXVII International Conference on High Energy Physics (ICHEP), July 1994, Glasgow, Scotland.

[5] M. Battle *et al.* (CLEO Collab.) in Proceedings of the joint Lepton-Photon and Europhysics Conference on High-Energy Physics, Geneva 1991.

[6] J. Hewett, Phys. Rev. Lett. **70** (1993) 1045; V. Barger, M. Berger, and R. J. N. Phillips, Phys. Rev. Lett. **70** (1993) 1368.

[7] J. L. Lopez, D. V. Nanopoulos, and G. T. Park, Phys. Rev. D **48** (1993) R974; G. T. Park, P. 70, the Proceedings of the HARC workshop "Recent Advances in the Superworld", The Woodlands, Texas, April 1993; J. L. Lopez, D. V. Nanopoulos, G. T. Park, and A. Zichichi, Phys. Rev. D **49** (1994) 355.

[8] G. T. Park, Phys. Rev. D **50** (1994) 599; G. T. Park, Mod. Phys. Lett. A **9** (1994) 321.

[9] D. Schaile, talk given at 27th International Conference on High Energy Physics, Glasgow, July 1994.

[10] G. Altarelli, R. Barbieri, and F. Caravaglios, Nucl. Phys. B **405** (1993) 3.

[11] G. Altarelli, CERN-TH.6867/93 (April 1993).

[12] B. Grinstein and M. Wise, Phys. Lett. B **201**, 274 (1988); B. Grinstein et. al., Nucl. Phys. B **399**, 269 (1990); T. Rizzo, Phys. Rev. D **38**, 820 (1988); C. Geng and J. Ng, Phys. Rev. D **38**, 2858 (1988); W. Hou and R. Willey, Phys. Lett. B **202**, 591 (1988).

[13] S. Bertolini, F. Borzumati, A. Masiero, and G. Ridolfi, Nucl. Phys. B **353** (1991) 591.

[14] B. Grinstein, R. Springer, and M. Wise, Phys. Lett. B **202**, 138 (1988); R. Grigjanis et. al., Phys. Lett. B **213**, 355 (1988); Phys. Lett. B **224**, 209 (1989); M. Misiak, Phys. Lett. B **269**, 161 (1991); M. Misiak, Nucl. Phys. B **393**, 23 (1993).

[15] R. Barbieri and G. Giudice, Phys. Lett. B **309** (1993) 86.

[16] A. Buras, M. Misiak, M. Münz and S. Pokorski, Nucl. Phys. B **424**, 374 (1994).

[17] V. Barger, J. Hewett, and R. J. N. Phillips, Phys. Rev. D **41** (1990) 3421.

[18] J. Bernabeu, A. Pich, and A. Santamaria, Phys. Lett. B **200** (1988) 569; W. Beenaker and W. Hollik, Z. Phys. C40, 141(1988); A. Akhundov, D. Bardin, and T. Riemann, Nucl. Phys. B **276** (1986) 1; F. Boudjema, A. Djouadi, and C. Verzegnassi, Phys. Lett. B **238** (1990) 423.

[19] A. Denner, R. Guth, W. Hollik, and J. Kühn, Z. Phys. C51, 695(1991).

[20] A. Djouadi, G. Girardi, C. Verzegnassi, W. Hollik, and F. Renard, Nucl. Phys. B **349** (1991) 48.

[21] M. Boulware and D. Finnell, Phys. Rev. D **44** (1991) 2054.

[22] C. Ahn, B. Lynn, M. Peskin, and S. Selipsky, Nucl. Phys. B **309** (1988) 221.

[23] G. Altarelli, talk given at the 1st International Conference on Phenomenology of Unification from Present to Future, Rome, CENR-TH.7319/94 (June 1994).

[24] A. Buras et al., Nucl. Phys. B **337** (1990) 284.

[25] We have assumed that the updated analysis would not change the conclusions in Ref[17] drastically.

Figure Captions

- Figure 1: The regions in $(m_{H^\pm}, \tan\beta)$ plane excluded in 2HDM by the new CLEO bound at 95%C. L. $B(b \to s\gamma) < 4.0 \times 10^{-4}$, for $m_t = 163, 176\,\mathrm{GeV}$. The excluded regions lie to the left of each dotted curve. The excluded regions by the latest LEP value at 95%C. L $\epsilon_b = -0.00733$. lie below each solid curve. The values of m_t used are as indicated.